

N 9 4 - 1 8 5 5 1

Sverdrup
Technology Inc.

Internal Fluid Mechanics Division



186468

P-11

**Analysis of Supersonic Flows using k- ϵ Model and the
RPLUS code; Progress towards High Speed Combustor
Analysis.**

by J. Lee

Sverdrup Technology Inc./CFD Branch
for Workshop on Computational Turbulence Modeling
Sept. 1993



Outline

- Problem of Interest - High Speed Combustor Flow Fields
 - Parameters need to be Resolved
 - Key Problems of Interest
- k- ϵ Model and RPLUS code
 - Numerical Technique
 - Models being Tested
 - Some Results
- Summary

2



Problem of Interest

- Analysis of Chemically Reacting flow inside of Supersonic RAM jet Combustors-Two Key Parameters need to be determined.
 - Mixing/Combustion Efficiency
 - Kinetic Energy Efficiency (Flow Losses)
 - Inlet, Diffuser, etc..
- In order to do get some ideas on those parameter following (Potential Loss Mechanisms) must be modeled/determined correctly.
 - Mixing, Shear,
 - Turbulence, Vorticity,
 - Shock-waves, Heat Transfer,
 - Fuel Injector Drag, Poor Wall Pressure Integral,
 - Chemical Dissociation.

from 2nd JANNAF workshop on SCRAMjet Combustor performance workshop

3



Mixing and Injector Design

- At High Mach Number($M \sim 5.0 +$).
 - Doesn't mix well!
 - The Natural diffusion mechanism very INEFFECTIVE.
 - Fuel Residence Time Extremely Small- Even with Fast Fuel Such as H_2
- Geometrical Complexities
 - To induce Favorable mixing and Flame holding features
 - Back-Step/Stream Wise Vorticity/Shock-Wave Interactions
 - Unsteady Mechanism also being Envisioned as mixing enhancement
 - Kumar, Bushnell and Hussani(1987)

4



Introduction of Externally Generated Mixing Enhancements

- Some External helping hand needed \Rightarrow Modeling Difficulties.
- Externally Generated Vorticity Through Sweep angle of the Ramp injector.
 - Davis(1990), Riggins and McClinton(1990), Drummond(1991).
- Multiple Transverse Injection.
 - Hartfield et. al. (1991)
- Flame holding tricks/ Back-step with Recirculation.
 - Hartfield et. al.(1991)
- Simplified analysis of these features very difficult because of limited database/understanding (Attempts are being made using CFD solutions- JANNAF Combustor Subcommittee).

5



Numerical Modeling(CFD) of Combustor Flow Field

- CFD Analysis.
- Numerical Modeling=> Overall Analysis of performance => Difficult
- Overall Laminar Flow Fields with Complex Geometry/Finite Rate Chemistry has been demonstrated.
- Finite Rate Chemistry Model- Yoon and Shuen(1989)
- Multiple Grid Blocks- Moon (1991)
- Analysis of a typical Injector Configuration with Zero Equation Turbulence Model using LU Scheme(RPLUS) code- Lee(1993)

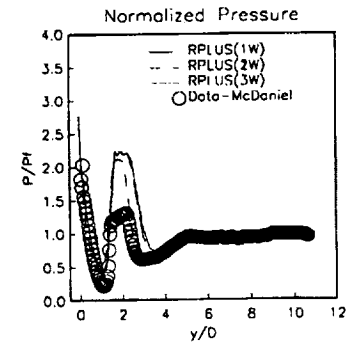
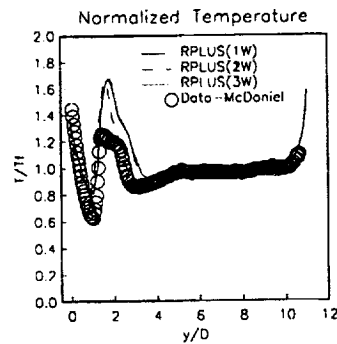
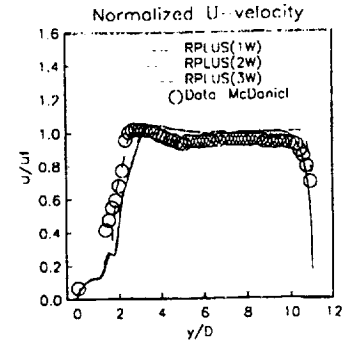
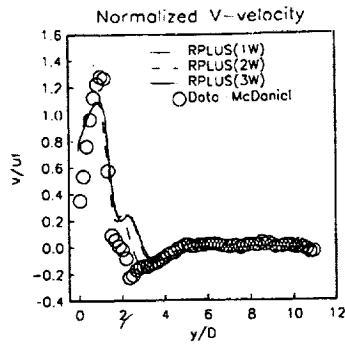
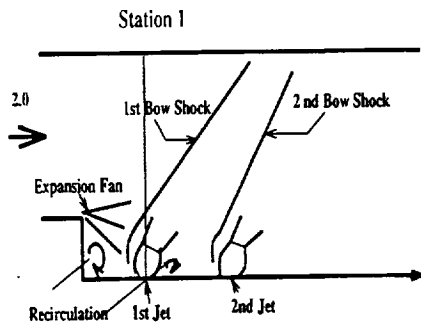
6



Simple Zero Equation Turbulence model with multiple wall scaling Buleev-Inverse square rule can be used to extend model in to three-dimensional form. (Lee (1993))

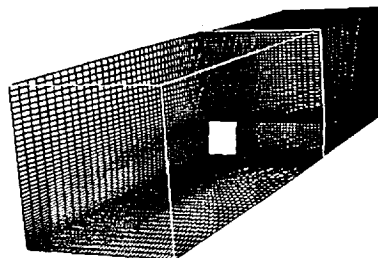
- Good News/Bad News
- Typical velocity profiles can be reasonably predicted.
- Over all combustor flow features can be reasonably predicted.
- Near-wall temperature characteristics near non-equilibrium region around the injector and separated flow were poorly predicted.
- Overall spreading behavior of shear region poorly predicted.
- Two Equation Transport Turbulence Model has the potential to ease some of these difficulties.

7

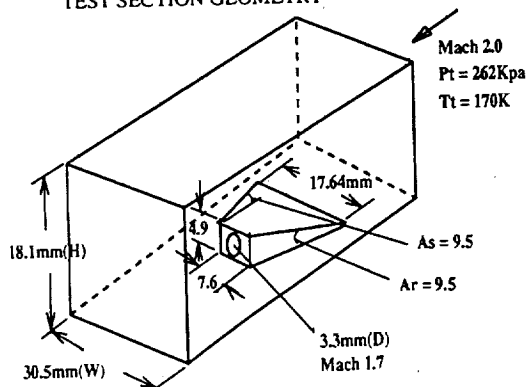


THREE-BLOCK GRID SYSTEM

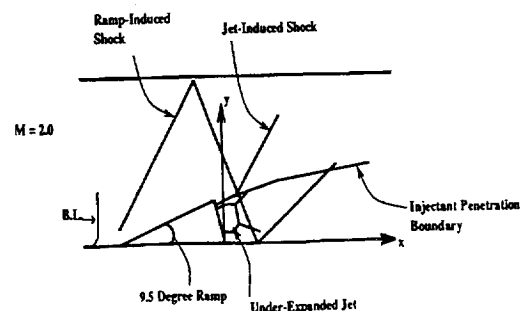
HARTFIELD ET. AL. (1990)

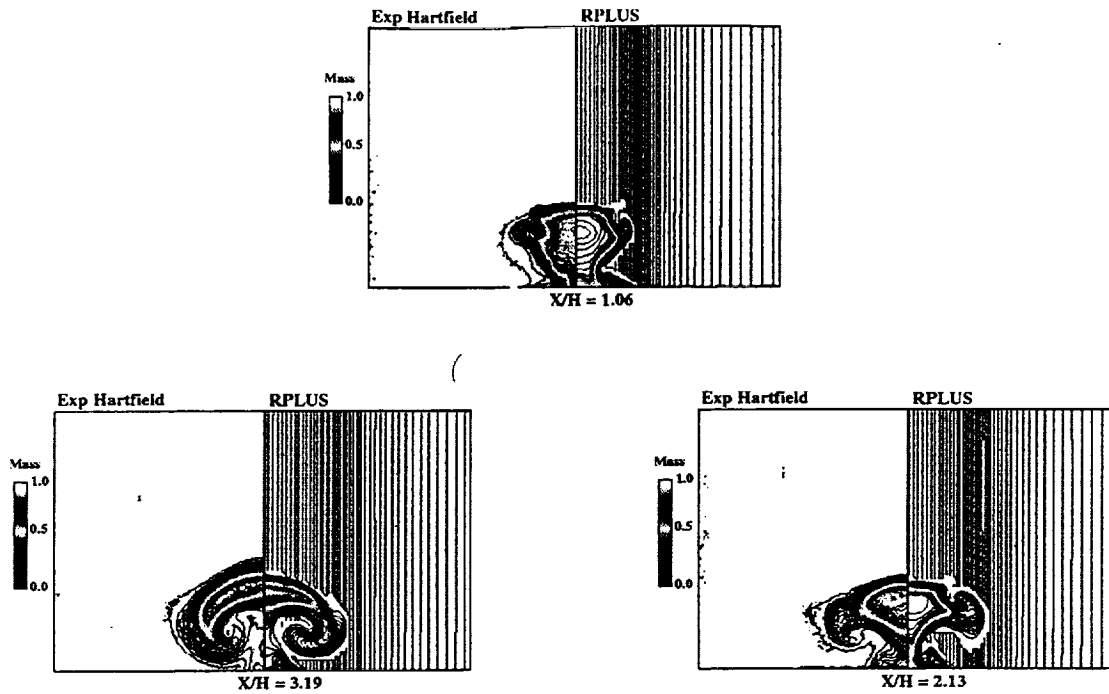


TEST SECTION GEOMETRY

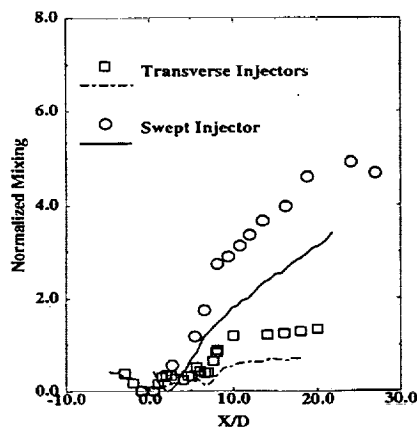


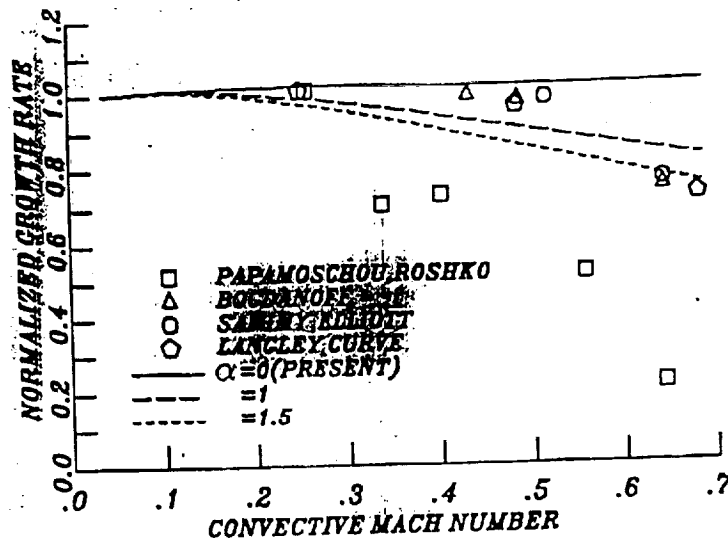
FLOW SCHEMATIC





Mixing Efficiencies





GROWTH RATE VS. COMPRESSIBILITY EFFECT

DR. H. LAI

Sverdrup

Technology Inc.

Internal Fluid Mechanics Division



Two Equations Transport Turbulence model are being Analyzed

- High speed turbulence models are some what Deficient (The deficiencies are well documented(Marvin(1986), Wilcox(1993))).

Effect of Compressibility

An-isotropy (Low/High Speed).

Non-Equilibrium Flow Features (Low/High Speed).

Near-Wall Flow(Low-Reynolds Number Features (Low/High Speed)).

Inflexibility of handling Complex Geometry- Invariance Principle (Low/High Speed)

Large Dependence in the Numerical Methods Used (especially elliptic Solvers).

Appropriate Initial/Boundary Conditions

Etc ...



K-ε Model-RPLUS Development

- **LU Based k-ε Model Solver-De-coupled Approach.**

Mean-Turbulence Transport Equations

LU-SSOR- Yoon and Shuen- Explicit Terms Centrally Differenced

LU-SW -Steger and Warming- Explicit Terms Upwind Differenced

k-ε Models

Convective Terms + Diffusive Terms + Source Terms = 0.0

Model Only differ in Low-Reynolds Number Character.

Models performance are being Evaluated.

Implicit Source Term Handling Strategy also Being Studied

10

k-ε Turbulence Models being studied for potential used in Three Dimensional RPLUS Code.

- **Low-Reynolds Number Model plus Dilatational Terms**

Chien (1976)

Launder-Shima(1976)

Shih(1990)

Various CMOTT derivatives of k-ε Model

Realizability

Invariance

Simplified Boundary-Conditions

- Performance of the Low-Reynolds number K-ε model in low-Mach number flows have been demonstrated (Patel, Rodi and Scheuerer(1985), Steffen(1993), Launder(1992)).
- Some of the Potential Difficulties in high speed turbulence model are well documented (Marvin(1993), Coakley and Huang(1992)).

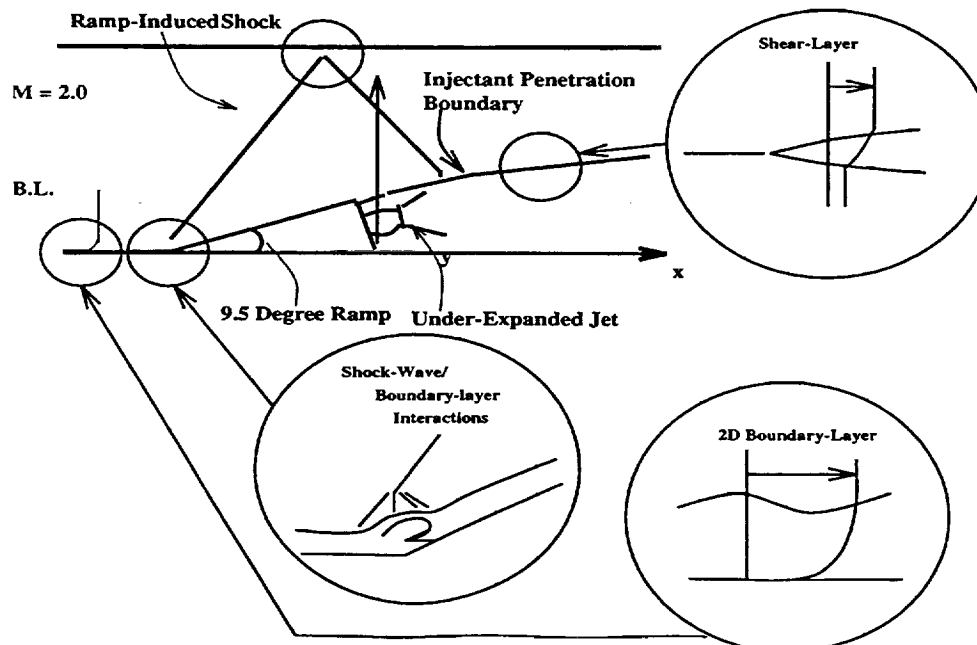
11



Evaluation and Development of the RPLUS/k- ϵ Model Solver

- Various 2D-3D problems are being studied to optimize the numerical method and to Evaluate model performance in supersonic flows in context to the LU based numerical Technique.
- Simple 2D k- ϵ models are also being used to study various components of the flowfield generated by the complex combustor geometry previously shown.
- Studying the Numerical method/Model Behavior/Model Performance.
 - 2D Supersonic Turbulent Boundary-Layer- Skin Fraction/Heat transfer (NASA Ames Database).
 - 2D Supersonic Shock-Wave Boundary-Layer Interaction- Skin fraction/Heat -Transfer/ Shock-wave(A. Smits (1990's))
 - 2D Shear-Layer - Mixing (H. Lai(1993))
 - 3D Fin/Flat Plate Interaction- 3D Corner Flows-Interaction Developed through a Fin generated Shock-Waves. (D. Davis(1992))

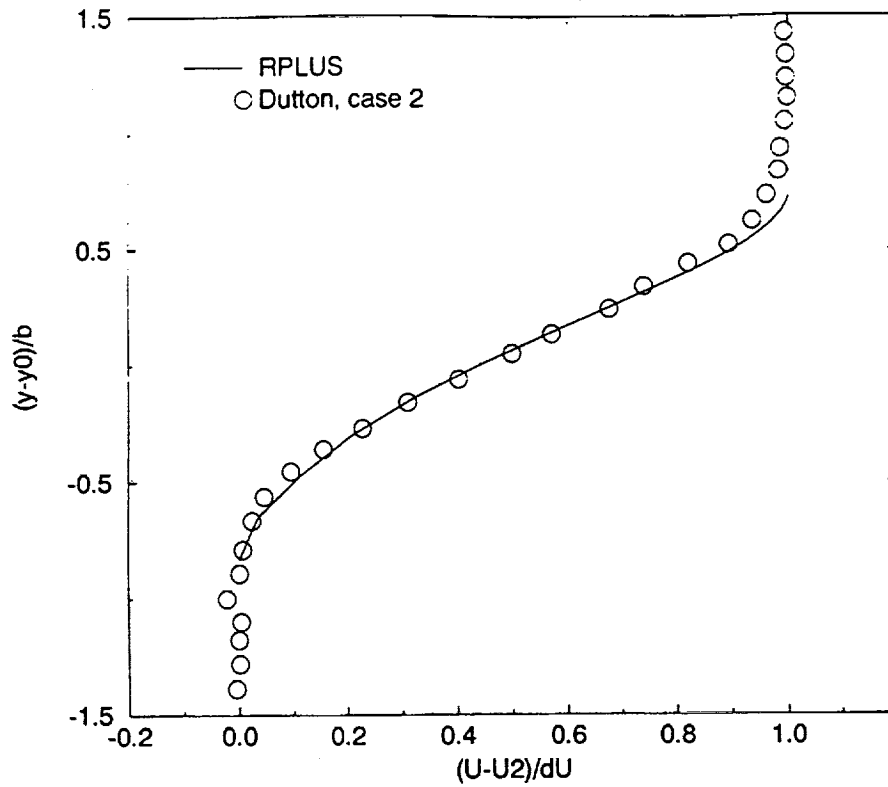
24



25

Supersonic Mixing Layer

RPLUS vs. Dutton (case 2)



B. DUNCAN



Sverdrup

Technology Inc.

Internal Fluid Mechanics Division

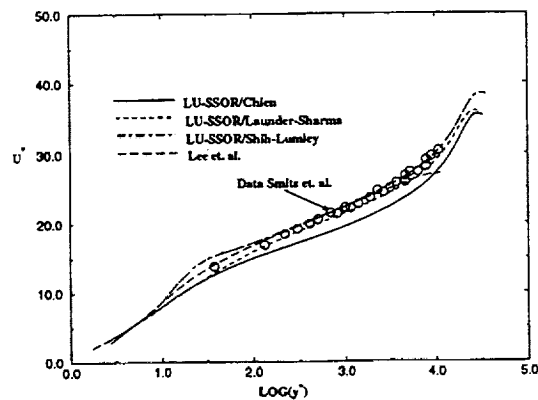


Boundary Layer

Mach 2.87

$Re/m = 6.3 \times 10^7/m$

Law of Wall Profile

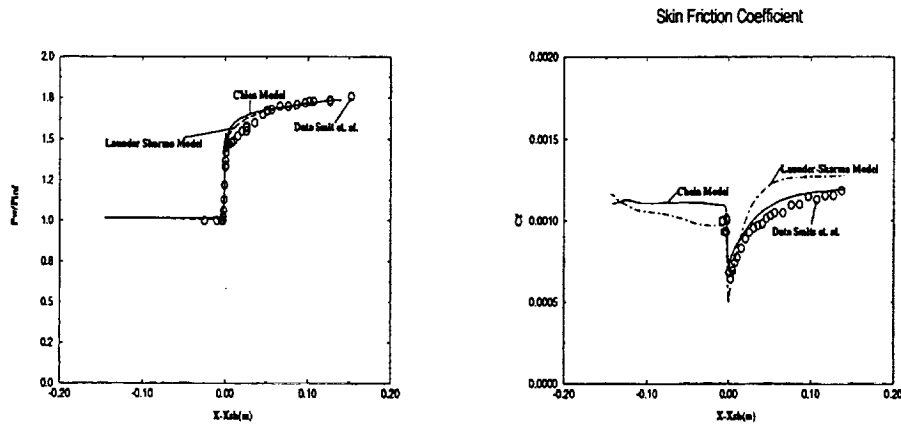




Turbulent Shock-Wave/Boundary Interactions

Mach 2.87

Ramp Angle = 8.0 degrees



Other Factors

- Optimum Numerical Strategy with in LU frame work.
- Effects of Initial condition.
- Modeling of Compressibility terms/Dilatational terms.
- Modeling of Turbulent terms in the Finite Rate Chemistry Model.
Anisotropy of Turbulence
- Effects Upstream and Down stream Influences (Inlet(K. Kapoor) and Diffuser(?)).
- Chemistry-Turbulence Model Interactions (A. Hsu-PDF).
- Numerical Robustness(A. Suresh).